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Deep Borehole Instrumentation along San Francisco Bay Bridges

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Abstract

This is a progress report on the Bay Bridges downhole network. Between 2 and 8 instruments have been spaced along the Dumbarton, San Mateo, Bay, and San Rafael bridges in San Francisco Bay, California. The instruments will provide multiple use data that is important to geotechnical, structural engineering, and seismological studies. The holes are between 100 and 1000 ft deep and were drilled by Caltrans. There are twenty-one sensor packages at fifteen sites. The downhole instrument package contains a three component HS-1 seismometer and three orthogonal Wilcox 731 accelerometers, and is capable of recording a micro g from local M =1.0 earthquakes to 0.5 g strong ground motion form large Bay Area earthquakes.

Preliminary results on phasing across the Bay Bridge, up and down hole wave amplification at Yerba Buena Island, and sensor orientation analysis are presented. Events recorded and located during 1999 are presented. Also, a senior thesis on the deep structure of the San Francisco Bay beneath the Bay Bridge is presented as an addendum.

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Introduction

This is a progress report on the Bay Bridges downhole network. The Bay Bridges down hole network consists of recordings in bore holes that are drilled 100 ft into bedrock along and in the San Francisco Bay (Figure 1). Between 1 and 8 instruments have been spaced along the Dumbarton, San Mateo, Bay, Carquinez, and San Rafael bridges. Tables 1 - 5 list recording site information, and Figure 1 shows instrument locations. In addition, two vertical arrays exist at the Dumbarton bridge with additional sensors at the surface and at 200 ft (Table 1). Two sensors are currently located at the surface at the Bay Bridge and are waiting drill holes. Prior to this study few seismic recording instruments existed in bedrock in San Francisco Bay. This left a recording gap for engineering studies of the Bay bridges and in seismicity studies of the Bay Area. Figure 2 shows earthquakes recorded by instruments along the San Francisco/Oakland Bay bridges during 1999. The Bridges network is part of a larger Hayward Fault Digital Network, see Figure 1.

There are six primary areas of research by LLNL that will be enhanced by the bore hole instrumentation: 1) developing realistic predictions of strong ground motion at multiple input points along long span bridges, 2) examining ground motion variability in bedrock, 3) calibrating soil response models, 4) developing bridge response calculations with multiple support input motions, 5) evaluate the seismicity of potentially active faults in the San Francisco Bay, and 6) record strong ground motion.

Key to these studies is LLNL's effort to exploit the information available in weak ground motions (generally from earthquakes < M=3.0) to enhance predictions of seismic hazards. Although strong ground motion recordings are essential to calibrate models and understand the hazard of future earthquakes, we can obtain weak ground motion data immediately, whereas it may be years before strong motion data is recorded. Following is an expansion of research goals utilizing recordings from the Bridges Network.

1) prediction of strong ground motion: LLNL is developing a methodology of using weak ground motion to synthesize linear response strong ground motion and incorporating this with constraints on fault rupture scenarios to predict strong ground motion. These computations provide estimates of the full wavetrain ground motion at multiple points along long span structures.

2) ground motion variability: Recent studies have demonstrated the high variability of strong ground motion with site conditions. Recordings along Bay bridges will be used both to improve calculations of ground motions for bridges, and to research the spatial sensitivity and significance of site variability to structures.

3) soils response: LLNL is researching means of using weak ground motion to constrain soils models for non-linear computations. Current research has shown that low strain constitutive properties are significant to non-linear ground motion computations, and that these values can be significantly improved by an iterative process of matching weak motion solutions.

4) bridge response calculations: Current developments in structural dynamics allow non-linear, three-dimensional calculation of bridge response. This requires realistic full wavetrain input ground motions. LLNL is conducting research on the sensitivity of synthetic ground motions to accurate non-linear computations, and the significance of utilizing multiple support input calculations.

5) seismicity: Location of small earthquakes within the Bay that may indicate the existence of active faults will be made possible with the instrumentation. Very small earthquakes (M<2) cannot be recorded adequately to determine accurate locations by regional networks.

6) *strong ground motion:* Strong ground motion from previous earthquakes gives a good indication of what might be expected from future earthquakes. In addition recent earthquakes have demonstrated the high variability of strong ground motion so that an array of strong ground motion recordings will give a better understanding of the ground motion variability from future earthquakes.

Instrumentation

The down-hole sensor package is manufactured at LBL under the direction to Dr. Tom McEvilly, and is the same package used by the USGS and LBL for the Hayward Fault Digital Recording Network. This package contains three orthogonal Oyo HS-1 4.5 Hz geophones and a three orthogonal Wilcoxon 731s 10v/g accelerometers. The dynamic range of the Wilcoxon package is from a micro-g to 0.5 g acceleration, and is flat to frequency response from 0.1 to 300 Hz. This allows recording of M =1.0 to 0.5 g strong ground motion form large Bay Area earthquakes. Typically, the Wilcoxon's are recorded over two dynamic ranges to capture weak and strong ground motions, and HS-1's are used as a backup for weak ground motion recording. Portable Refraction Technology 72A Data Acquisition Systems with 16 bit resolution and 200 Hz sampling are used to record the data at most sites. Three sites utilize Quantera-4120 24-bit resolution data loggers with 500 Hz recorders. The data is processed and managed at UC Berkeley. Tables 1-5 list site and instrumentation information for the recording sites.

Sensor Orientation

We obtained an estimate of the orientation of the sensors by examining P-wave particle motion. We rotated the horizontal components until all P-wave motion was on one horizontal component, and assumed this was in a radial direction from the earthquake. Table 7 lists events used and calculated orientations at the sites; the average values are listed in Tables 1-5. Event information is listed in Table 7.

Preliminary Results

Bay Bridge

Site Response Transfer Function at Yerba Buena Island

We identified 10 events that were recorded on both the top and bottom of borehole sites at Yerba Buena Island, BE2U and BE2D (Table 8). Table 1 list the event information. We averaged the two horizontal components at each site and performed a spectral ratio. Figure 3 shows the horizontal components for up (BE2U) and down (BE2D) recordings for event 98/12/04, and their spectra ratio. Figure 4 shows the mean and +/- standard deviation of the spectral ratios of the 10 events. The ratio is near one for frequencies less than about 5 Hz and this is the frequency range where the free surface effect is not occurring for long period arrivals. Amplifications above a factor of two occur at higher frequencies and this is due to the geologic site response of the weathered rock. Figure 5 show the effect of applying the mean response relation to a single component for event 1998/12/04.

Figure 6 shows amplifications from the bottom of the borehole at site W02 to the rock outcrop at SFA (anchorage site) at the San Francisco anchorage at western end of the SFOBB. The valid frequency range of the data is from 0.7 to 10 Hz due to surface noise at SFA. However, the differences in the spectral amplitudes are minimal over this frequency range and suggest that there is little amplification for seismic waves from the bottom of the borehole to the rock outcrop nearby at this site. All relations discussed here are preliminary and substantial more analysis is need to finalize results. However, relations such as these can establish the usefulness of borehole recordings for studying site response.

Phasing and coherency relations for the Bay Bridge

Figure 7 shows recorded ground motion from a magnitude 4.1 earthquake (37.92oN 122.30E h=6.8, UCB Seismographic Stations) along the Hayward fault at all sites (except E23) across the Bay Bridge. Analyses of this and other data can provide explicit relations for wave passage, phasing and coherency effects along the bridges. Figure 8 shows lagged coherency (wave passage effects removed) relations along the Bay Bridge obtained from small earthquakes (Mualchin et al., 1999).

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Table 1: Dumbarton Bridge Recording sites

i.d.	sensors	latitude	longitude	depth (m)	sensor h1, h2 + 090	Recording
Pier 01		37.49947	122.12755			
DWA,	S-13			00.0 m, abut.	N320°E	07/94 - 09/94
DWS	Wil-731-200, HS-1			01.5, Pier 01	000°	09/94 - 09/94
DWN	Wil-731-200, HS-1			71.6, "	---	09/94 - 09/94
DWB	HS-1, HS-1			228.0, "	033°	08/93 - present
Pier 27						
DMB	Wil-731,HS-1	37.50687	122.11566	189.2, Pier 27	N020°E	07/94 - present
CAP	Wil-731-200, HS-1	37.517	122.104	pile cap, Pier 27		07/92 - 11/92
Pier 44		37.51295	122.10857			
DES	Wil-731-200, HS-1			01.5, Pier 44	N000°E	11/94 - 09/94
DEM	Wil-731-200,HS-1			62.5	----	09/94 - 09/94
DEB	Wil-731, HS-1			157.9	097°	07/94 - present

Table 2: Bay Bridge Recording sites

i.d.	sensors	latitude	longitude	depth (m)	sensor h1, h2 + 090	Recording
SFA	S-6000	37.7861	122.3893	00.0 m,	N143°E	6/98-present
BBW2	Wil-731A,HS-1	37.79120	122.38525	57.6	N042°E	4/96-present
BBW5	Wil-731A,HS-1	37.8010	122.3737	36.3	N142°E	1/97-present
YBA	Wil-731A,HS-1	37.8094	122.3645	3.0	N150°E	6/98-present
BE2U	S-6000	37.81427	122.35815	0.00	N220°E	7/96-present
BE2D (YBIB)	Wil-731A,HS-1	37.81427	122.35815	60.96	N165°E	7/96-present
BE07	Wil-731A,HS-1	37.81847	122.34688	134.0	N117°E	2/96-present
BE17	Wil-731A,HS-1	37.82086	122.33534	160.0	N168°E	8/95-present
BE23	HS-1	37.82167	122.32867	150	N---°E	3/94-10/95

Table 3: San Rafael Bridge Recording sites

i.d.	sensors	latitude	longitude	depth	sensor h1, h2 + 090	Recording
P34	Wil-731A,HS-1	37.93583	122.44540	109.0 m		8/97-present
P58	Wil-731A,HS-1	37.93372	122.41313	44.0 m	N0°E	6/97-present

Table 4: San Mateo Bridge Recording sites

i.d.	sensors	latitude	longitude	depth	sensor h1, h2 + 090	Recording
P343	Wil-731A,HS-1	37.59403	122.23242	298.0 m	N0°E	not recorded

Table 5: Carquinez Bridge Recording sites

i.d.	sensors	latitude	longitude	depth	sensor h1, h2 + 090	Recording
CRQB	Wil-731A,HS-1	38.05591	122.22402	-------	N0°E	6/98-present

Table 6: Sensor Orientation Calculations, Bay Bridge

Orientations of up on channel 2; ch3 = ch2 + 090; Channel 1 is vertical, positive down, except **	SFA**	BBW2	BBW5	YBA**	BE2D	BE2U	BE07	BE17	BE23
9812041216	N143E	N042E	N142E	N150E	N165E	N310E	N117E	N168E	
+prior 08/24/99 since 08/24/99 *prior 01/15/97 since 01/15/97	N131E N136E					 N143E N310E			
Vertical									
vertical: up on channel-1	UU	DD	DD	DD	DD	UU	DD	DD	

Reftek recorder: up on channel-3 is 180° from direction of arrow on exterior of S-6000 velocity sensor. Channel-2 is 090° less than channel 3; vertical is positive motion up, except for S-6000 recordings.

+Station SFA
Arrow prior to 08/24/99: N041E
Arrow 08/24/99 to present: N046E

***Station BE2U**
Arrow 06/07/96 to 01/15/97: N053E
Arrow 01/15/97 to 09/30/99: N220E

Events Recoded in the Study
Table 1:

Earthquake	Time	Latitude	Longitude	Depth	Mag
1998/12/23	11:18:04.19	37.9375	-122.1012	11.61	2.50
1998/12/29	10:01:21.81	37.0960	-122.0363	10.04	3.00
1998/12/29	12:38:12.37	37.0915	-122.0425	10.14	3.95
1998/12/29	12:41:22.93	37.0935	-122.0488	8.07	1.70
1998/12/29	12:41:39.22	37.0973	-122.0328	9.91	3.76
1999/01/12	19:24:07.13	37.2390	-121.6275	5.96	2.90
1999/01/24	23:53:29.82	37.8435	-122.0565	14.06	2.10
1999/01/26	06:02:42.51	37.9143	-122.2883	4.71	2.00
1999/01/27	03:58:42.90	37.2538	-121.6382	6.53	3.78
1999/02/04	00:19:36.92	37.1602	-121.5537	6.10	3.88
1999/02/04	00:21:41.20	37.1613	-121.5550	6.09	3.72
1999/02/07	12:10:33.17	37.9722	-122.0267	12.88	1.40
1999/02/19	02:42:21.19	37.8710	-122.2418	9.45	1.40
1999/02/22	02:03:37.42	37.8728	-122.2453	9.32	1.40
1999/03/06	20:17:13.70	37.8257	-122.0245	7.96	2.40
1999/04/04	08:03:37.16	37.5797	-121.6890	8.03	0.90
1999/04/04	11:06:43.12	37.9135	-121.9658	10.13	2.40
1999/04/19	19:03:50.35	37.9440	-121.9322	3.96	1.10
1999/05/02	05:42:43.44	37.2747	-121.9618	5.71	1.20
1999/05/02	08:24:52.89	37.1220	-121.5250	7.89	1.50
1999/06/02	03:23:37.76	37.8708	-122.2433	9.38	1.40
1999/06/18	03:34:42.17	37.3835	-121.7362	9.65	2.60
1999/06/23	23:48:10.36	37.8735	-122.2435	9.84	2.00
1999/07/04	11:29:00.01	37.6030	-121.9937	7.10	2.10
1999/07/20	22:35:04.66	37.6018	-121.6915	13.68	1.40

<04/04@0600

Events Recoded in the Study
Table 7:

Earthquake	Time	Latitude	Longitude	Depth	Mag
1999/07/24	05:28:12.70	37.7558	-122.1380	7.82	1.90
1999/08/12	08:16:37.44	37.8663	-122.2453	6.54	2.50
1999/08/13	19:46:21.73	37.8510	-122.2325	6.13	2.00
1999/08/18	01:06:18.93	37.9068	-122.6868	6.67	4.98
1999/08/18	06:44:09.00	37.9150	-122.6738	7.22	2.60
1999/08/23	01:19:26.55	37.4303	-121.6823	7.73	1.40
1999/09/22	22:27:13.10	38.3950	-122.6337	9.71	4.20
1999/10/13	01:04:22.91	37.8742	-122.2407	10.07	2.70
1999/10/14	12:40:14.50	37.1967	-122.5693	10.93	1.50
1999/12/01	17:23:48.90	37.9325	-122.2905	9.18	2.23

Table 8: Events for Site Response Study

Earthquake	Time	Latitude	Longitude	Depth	Mag	Fault
1998/10/20	12:46:18.87	37.878	-122.246	10.0	2.1	Hayward
1998/10/22	01:28:36.34	38.525	-122.303	8.3	3.0	Unknown
1998/11/03	06:02:16.32	37.876	-122.243	9.5	2.4	Hayward
1998/12/04	12:16:07.76	37.920	-122.290	6.8	4.1	Hayward
1999/01/26	06:02:42.51	37.9143	-122.2883	4.71	2.0	Hayward
1999/02/04	00:19:36.92	37.1602	-121.5537	6.10	3.88	Hayward
1999/04/04	06:00	37.	-122.			
1999/06/23	23:48:10.36	37.8735	-122.2435	9.84	2.0	Hayward
1999/08/12	08:16:37.44	37.8663	-122.2453	6.54	2.5	Hayward
1999/08/18	01:06:18.93	37.9068	-122.6868	6.67	4.98	San Andreas

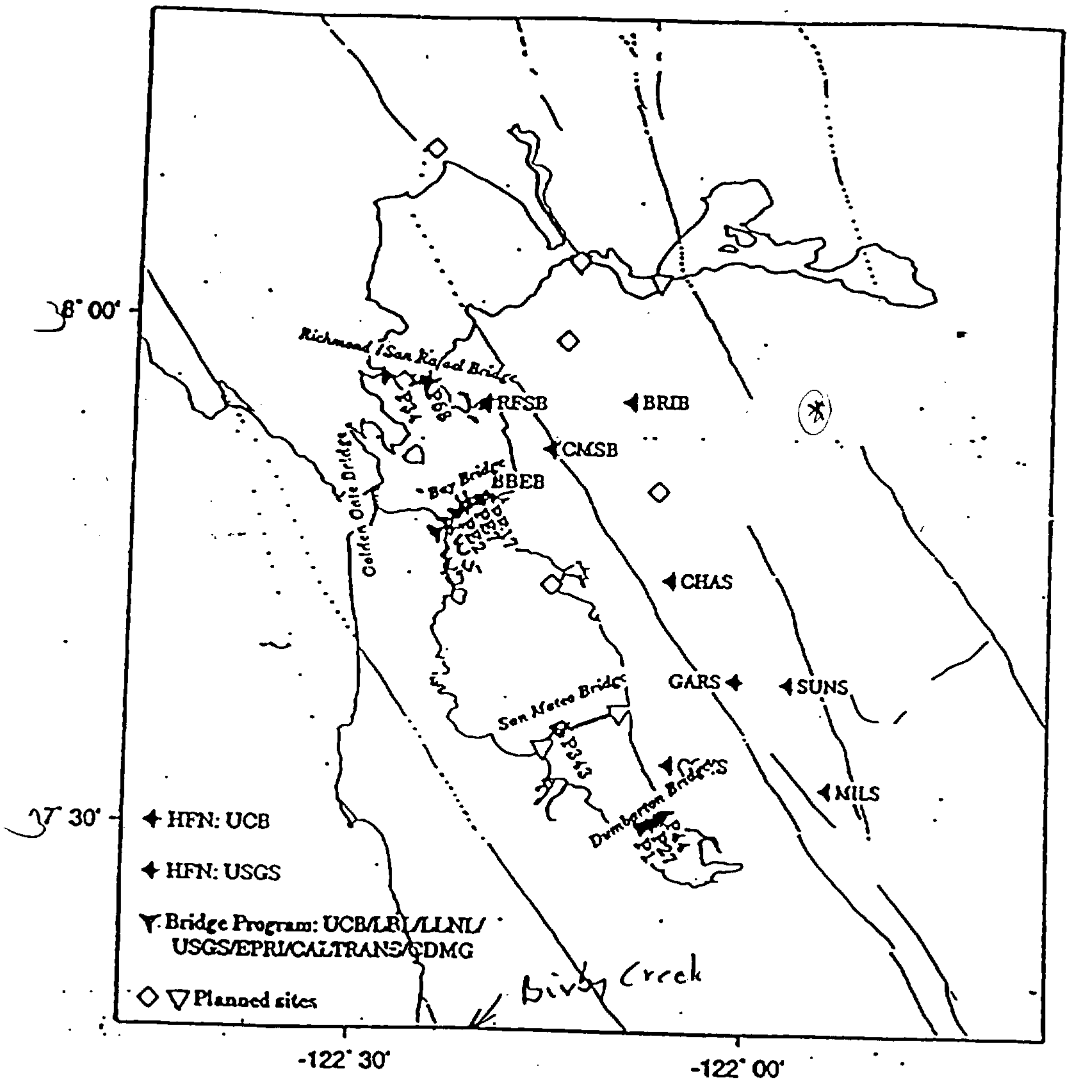


Figure 1. Station locations for the San Francisco Bay Bridges Network and the larger Hayward fault network.

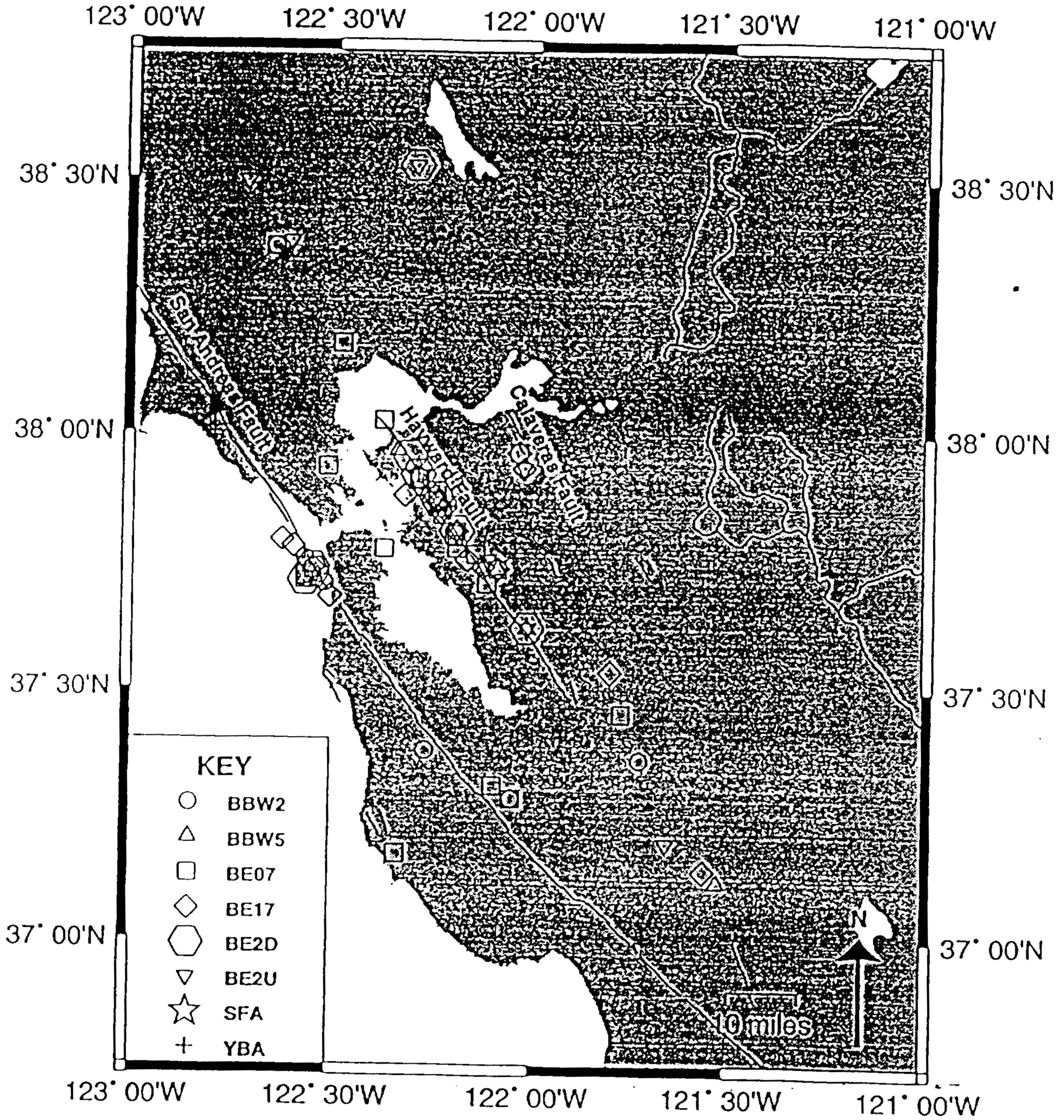


Figure 2 Locations of recent earthquakes recorded along the San Francisco Oakland Bay Bridge.

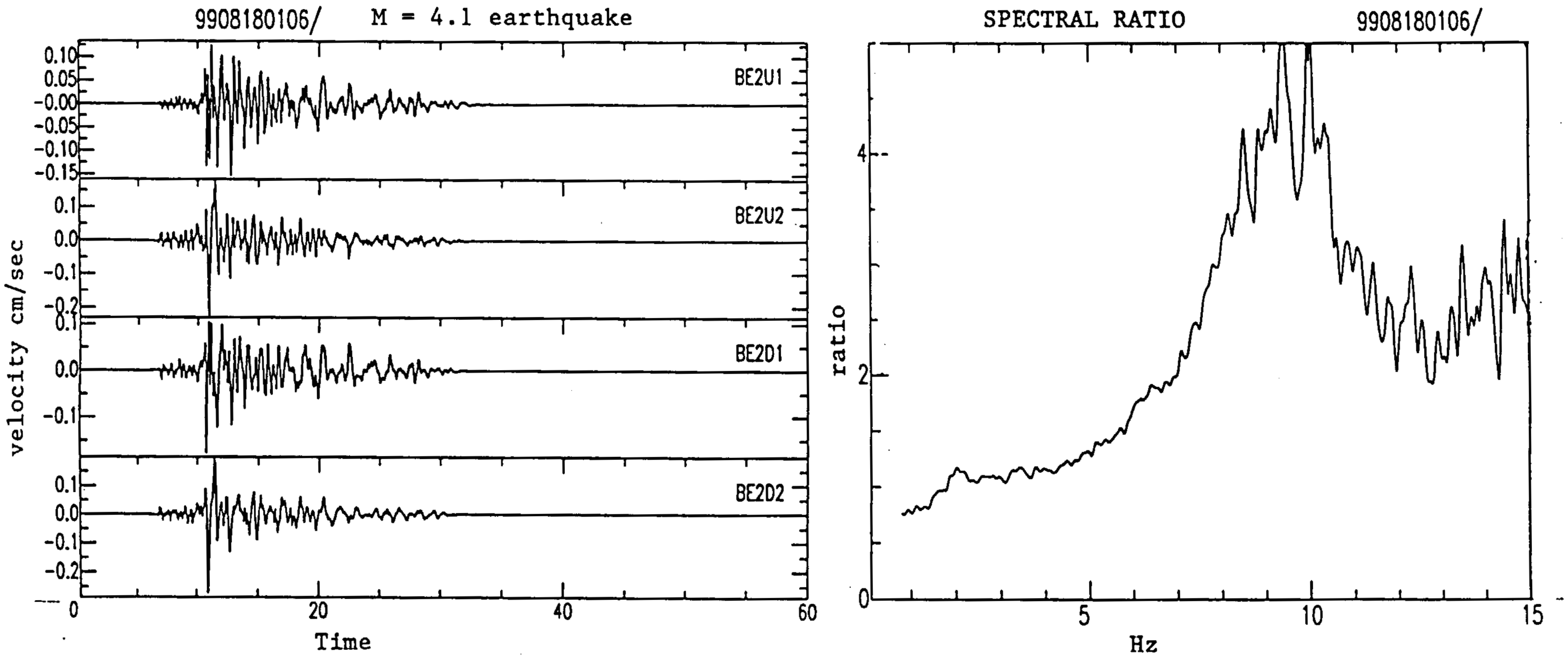


Figure 3. Surface (BE2U1 and BE2U2) and bottom of borehole (BE2D1 and BE2D2) horizontal recordings for a magnitude 4.1 earthquake, and the spectral ration of the average of the two components.

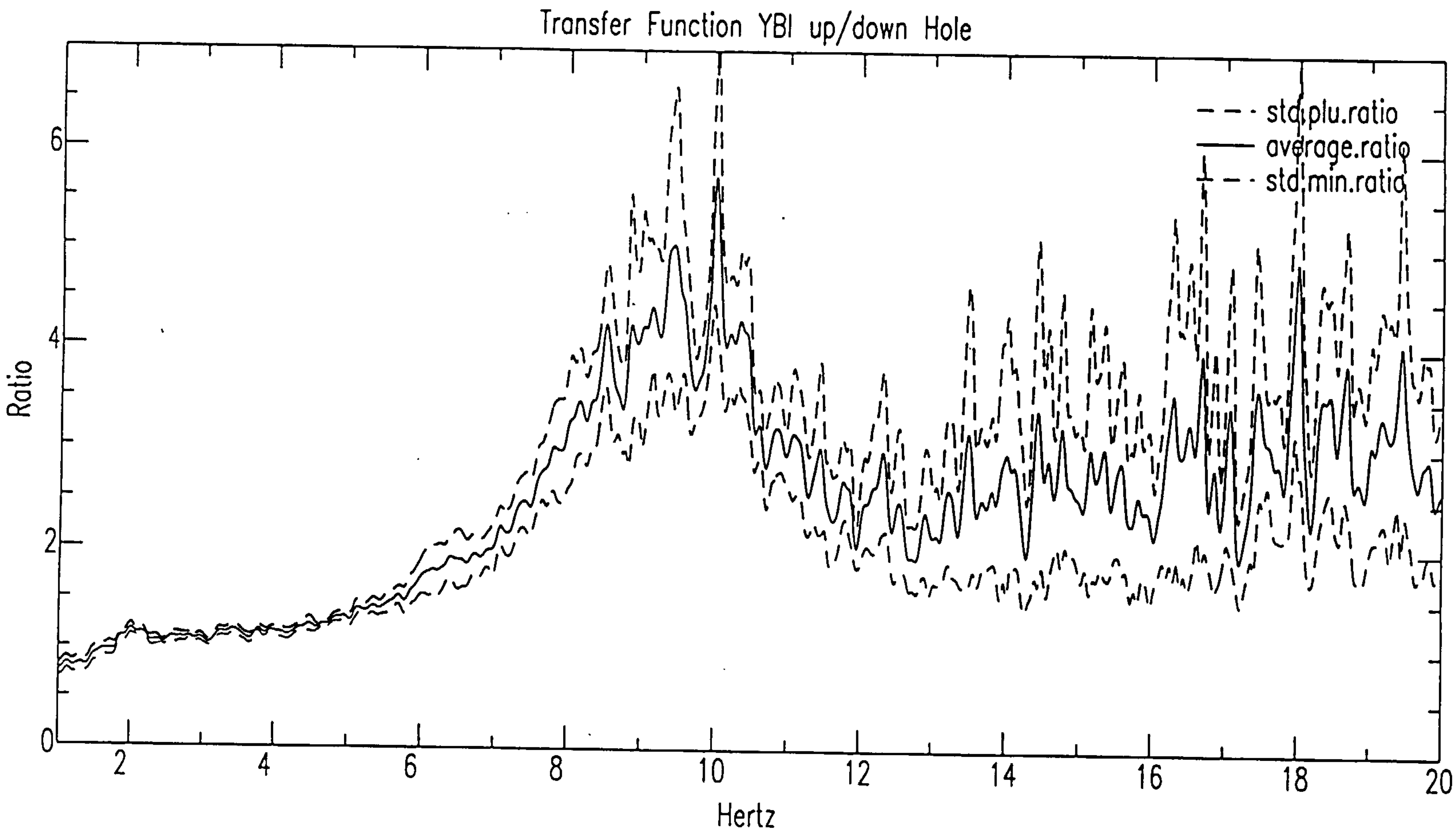


Figure 4 . Average spectral ratio from ten events (solid line) and plus and minus one standard deviation (dashed lines) for Yerba Island surface and borehole recordings.

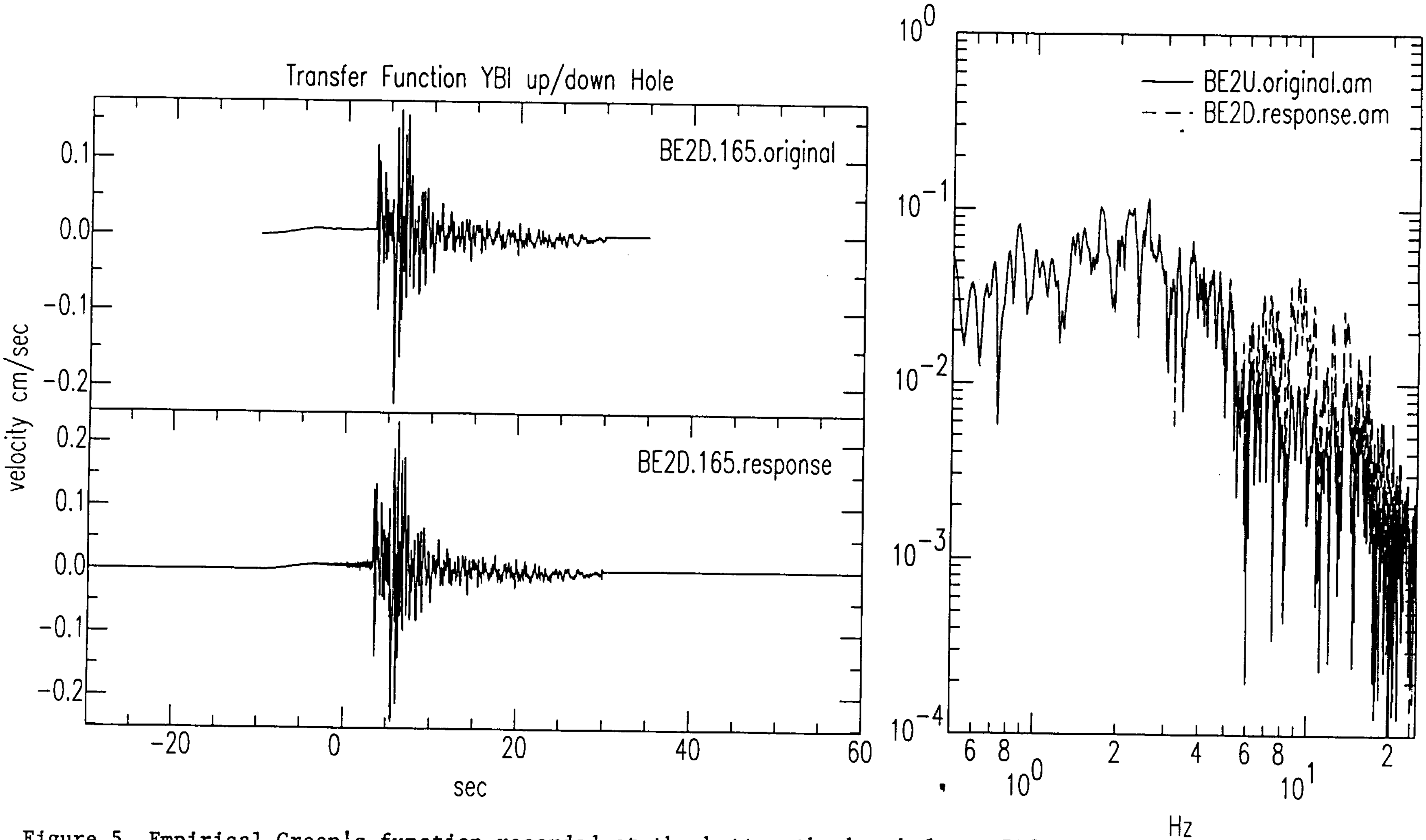


Figure 5. Empirical Green's function recorded at the bottom the borehole at BE2D, and convolved with the transfer function to create a surface recording.

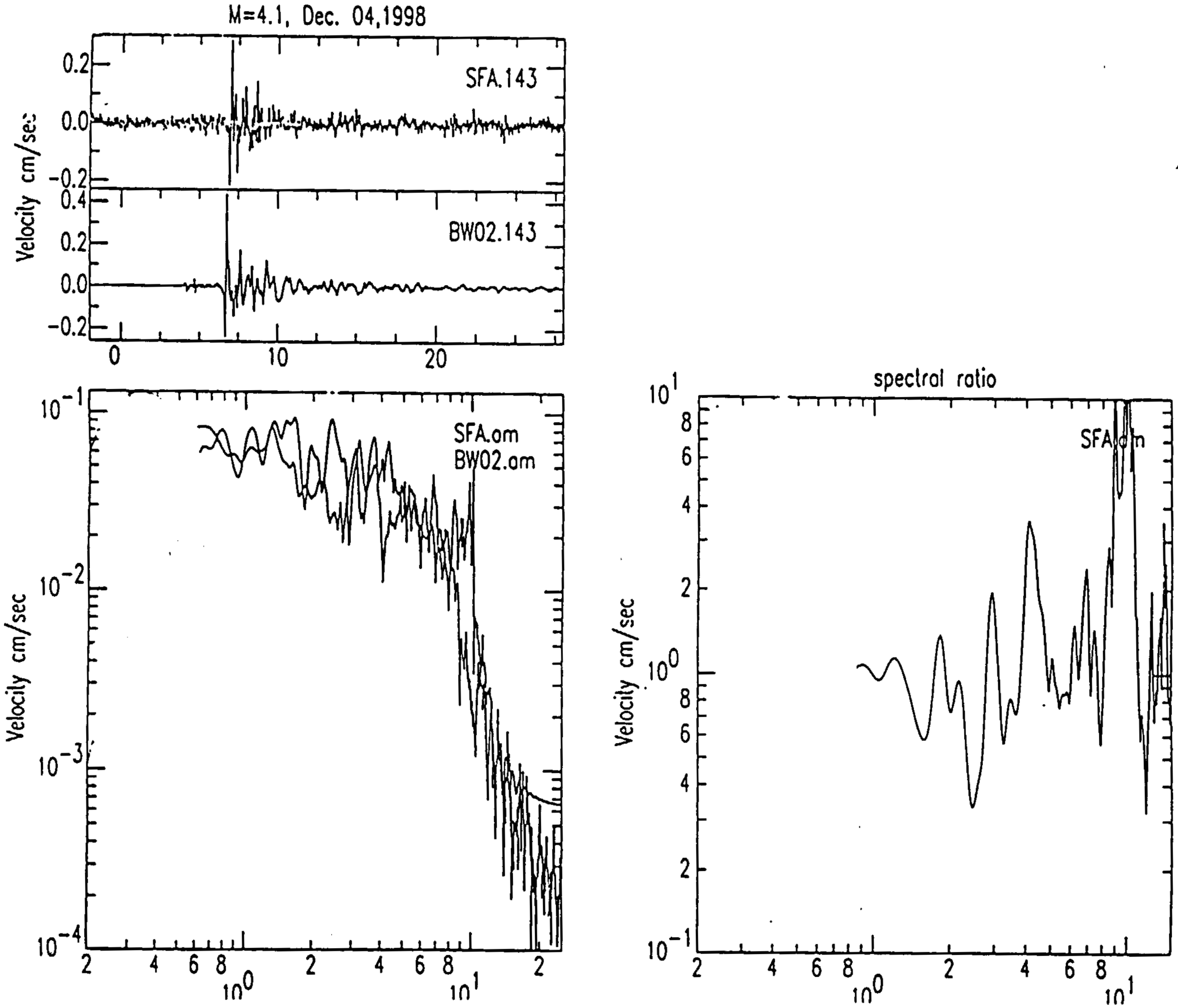


Figure 6 One horizontal component for surface recording at the San Francisco ancorage (SFA.143) and bottom of borehole recording at pier W02 (BW02.143) for a magnitude 4.1 earthquake, Fourier amplitude spectra and spectral ratio.

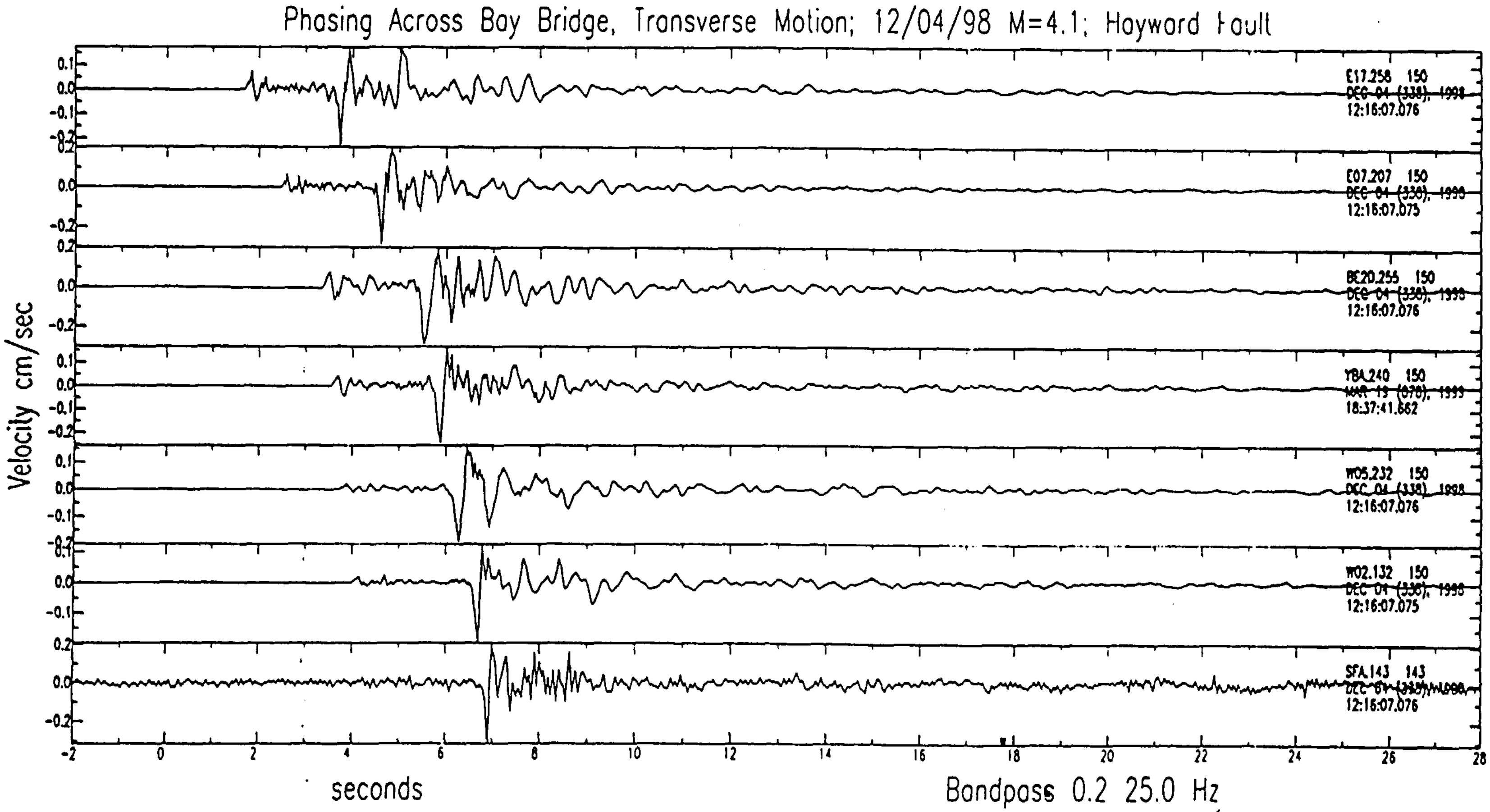
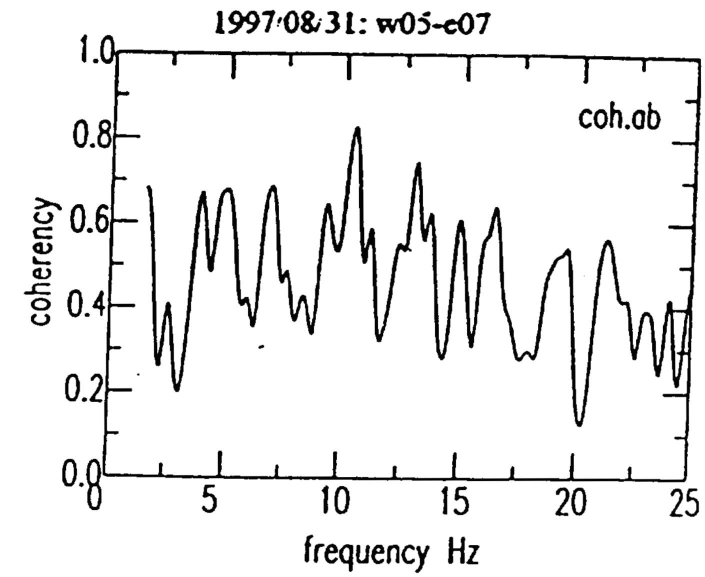
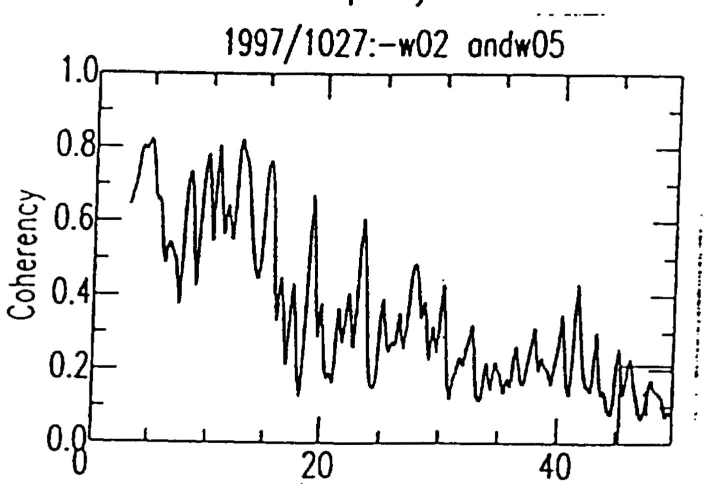


Figure 7. Recorded ground motion at sites across the SFOBB from a magnitude 4.1 earthquake located on the Hayward fault.





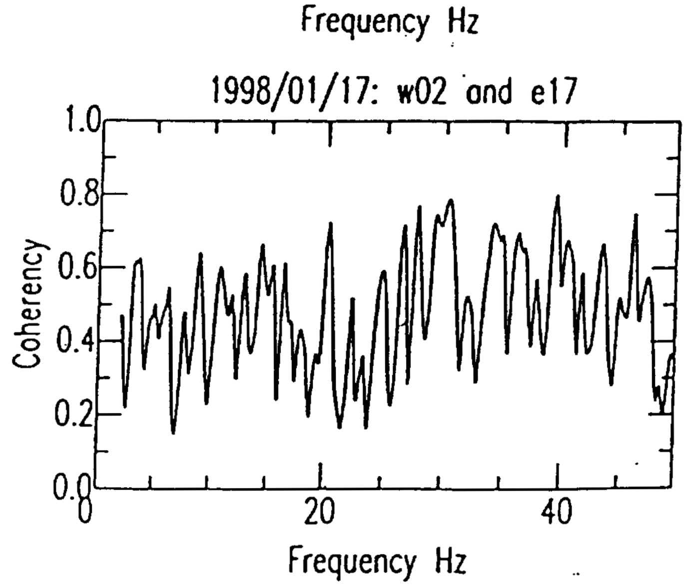


Figure 8 Coherency versus frequency.

Seismic Profile of the Franciscan Formation

Beneath the San Francisco-Oakland Bay Bridge,

San Francisco Bay, California

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Senior Thesis
Fall 1999

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Abstract

San Francisco Bay is a seismically active area bordered on the east by the Hayward Fault and the west by the San Andreas Fault. In 1996, a seismic network, consisting of eight instruments, was installed along the San Francisco-Oakland Bay Bridge by Lawrence Livermore National Laboratory and monitored by University of California, Berkeley to record and study strong ground motion earthquakes. Using data obtained by those stations from 1996 to December of 1998, a seismic velocity model proposed in 1993 by Thomas Brocher of the USGS, and a computer modeling program known as *Simul*, a preliminary seismic profile of the San Francisco Bay beneath the San Francisco-Oakland Bay Bridge was determined. The seismic velocities increased with depth from 4.74 km/s near the surface to as high as 6.1 km/s near the proposed bottom (15 km) of the Franciscan Formation. The profile also revealed, due to an increase in seismic velocity, four distinct discontinuities within the Franciscan Formation.

The San Francisco Bay Basin is located along the coast of Northern California. (See Figure 1). It is considered to be a complex estuary that includes San Pablo and Suisun Bays, covering an area of 568 square km. The Bay is bounded on the east and west by parallel ranges of the northwest trending Coast Ranges and by well known faults, the San Andreas on the west and the Hayward on the east.

The valley of the San Francisco Bay, or the whole basin where the present bay lies, appears to have been formed after the late Pliocene Epoch. The deposits that lie in the southern part of the bay valley (south of the Golden Gate) do not appear in the north suggesting that the valley formed to the east and was later extended towards the north.

The valley of the San Francisco Bay has been recognized as a structural valley, produced primarily by deformation. The warping and faulting caused the tilting of blocks along fault zones with the eastern depressed edge of the San Francisco-Marin block lying against the uplifted Berkeley Hills block. The valley is affected by the San Andreas fault system to the west and the Hayward fault system to the east. (See Figure 2). The development of the bay has a long history of substantial movement and seismic activity that is complicated by changes in sea level.

The most noteworthy aspects of the landscape were the result of changes in relative elevation. The lands to the east of the present bay was elevated, creating the hills which form the eastern edge of the San Francisco Bay valley. The lands immediately to the west of these rising hills lagged behind or were depressed to form the basin.

During the earlier part of the upper Pleistocene, the whole body of present hill lands, from the immediate Bay region to the Great Valley, were slowly uplifted allowing the main river (Sacramento River combined with the San Joaquin River) to maintain its course toward the ocean. (See Figure 3). During or near the same time, similar uplift occurred to the west of the Bay valley and the main river cut the Golden Gate canyon to a depth of more than 350 feet, thus creating the deepest part of the Bay. Today, strong tidal currents within the Golden Gate canyon prevent deposition of mud and thus allow the deepest portions of the canyon to be floored by bedrock. This bedrock is thought to represent the bottom of the ancestral main river as it flowed through the canyon towards the Pacific ocean.

Progressive flooding of the lower levels of the valley and canyon regions created the present San Francisco Bay and associated water bodies. The valley of the San Francisco Bay became a typical drowned valley; salt water invaded the region, and ocean tides were introduced into the system. The rise in sea level is thought to have occurred due to the melting of the ice sheets during the Pleistocene glacial period.

Throughout the Pleistocene, the eastern hills continued to rise as the valley region experienced relative depression. The stream downcutting processes were interrupted by the rising bay waters, thus indicating that the rise in sea level that produced the bay was a much shorter and more rapid process than that which elevated the hills.

During recent studies made in connection with the proposed San Francisco Bay crossings, numerous bore logs have revealed in detail the succession of formations which form the Bay floor. These formations can be divided into two distinct units; a bedrock unit and a younger unconsolidated sediment sequence consisting of the Alameda formation (oldest), San Antonio formation, Posey formation, Merritt formation, and the Bay Mud (youngest). (See Figure 4). Each unit is separated by an erosional interval or an unconformity.

The bedrock unit is composed of the Franciscan formation from the Mesozoic Era. The Franciscan formation consists of interbedded feldspathic sandstones, graywackes, siltstones, shales, limestones, radiolarian chert, metavolcanic lithics, and glaucophane schists. This formation was severely deformed, broken by faults, and heavily weathered prior to and during deposition. The total thickness of the unit has been estimated to be 15 km thick. (Brocher, 1993).

The Alameda formation was deposited during the Quaternary period. It is composed of layers of firm sand, silt, clay, and fine gravel. The formation commonly appears gray but can be greenish-gray or brownish-gray. The gravel consists of well-rounded pebbles, up to 1 inch in diameter, from the underlying

Franciscan formation. Plant fragments can be found throughout the unit but seem to be heavily concentrated within the upper portion. The unit ranges from 0 to 60 meters in thickness.

The most interesting characteristic of the Alameda formation is in the lower section. It consists of a clean layer of white volcanic ash. The ash is fine-grained dacitic vitric tuff which consists of over 95% fragments of clear glass and pumice, and 10% crystals of an acidic soda-lime feldspar, quartz, and hornblende. The volcanic layer is identical to that which occurs in the Merced formation. These are the only occurrences of volcanic ash found in the Bay deposits or in the adjoining Pleistocene deposits. The source of such material remains unknown.

The San Antonio formation can be divided up into three distinct layers. The first is composed of stiff silty clays. The second contains fine to medium-grained sands and silty clays, with abundant shell fragments. This layer has not been found on the western side of the bay. The third layer is composed of gray to greenish-gray fine-grained clays with interbedded layers of sands and sandy gravels. The sandy gravel contains pebbles from the Franciscan formation. The base of the formation is marked by a continuous layer of plant fragments. The overall thickness of the formation ranges from 4 to 37 meters.

The Posey formation is composed of firm clays and sandy clays in the upper portion and fine to medium-grained sands and clayey sands in the lower portion. In some places the Posey formation contains round pebbles, up to 1 inch in diameter, from the Franciscan formation. It is often mis-identified as the Merritt formation. The unit thickness ranges from 0 to 10 meters.

The Merritt formation was deposited after a period of extreme valley cutting due to stream erosion. It blankets the underlying Posey formation and fills the canyons. The Merritt formation is composed of well-sorted, medium-grained sand and in some areas consists of clay and well-sorted silt. The sorting indicates evidence for wind transport and the presence of well-sorted silt, similar to that of loess, is suggestive of glacial influences. The average thickness of the unit ranges from 0 to 18 meters.

The Bay underwent another period of extreme valley erosion before the deposition of the most recent unit, the Bay Mud. The Bay Mud blankets the surrounding lands and fills the canyons. The Bay Mud ranges in thickness from 0 to 30 meters and consists of soft mud. The mud is composed of silty clay, silty sand, and an occasional thinly interbedded layer of sand. The mud becomes firmer and contains less water as depth increases. The clay contains mica, chlorite, kaolinite, quartz, feldspar, and montmorillonite.

The San Francisco Bay has a complicated lithology that resulted mainly from stream processes. It has been severely altered by tectonic deformation and complex tidal currents. These currents continue to scour deep modern channels, rework sediments, and determine places of deposition even today.

Thomas Brocher, of the United States Geological Survey, through the San Francisco Bay area seismic imaging experiment (BASIX), did previous work in my study area in September of 1991. The goal of BASIX was to obtain deep crustal information that could be used to determine whether subhorizontal structures exist at depth.

During BASIX, reflection and refraction data were obtained in the Suisun, San Pablo, and San Francisco Bays and on the continental shelf near the Golden Gate Bridge. A research vessel was used to tow the seismic source, which consisted of a 12-element, 95.6-liter airgun array. Multichannel seismic reflection profiles were recorded by hydrophones deployed in the Bays. In addition, wide-angle refraction data were recorded at 70 onshore and offshore stations and on permanent earthquake seismic networks within Northern California.

The study revealed (see Figure 5) the presence of a lower crustal reflector, identified as the Conrad Discontinuity, at a depth of 15 kilometers beneath the San Francisco and San Pablo bays, which Brocher presumes to be the base of the Franciscan Formation. The high amplitude reflection had a two-way travel time of 6 seconds, which correlates to approximately 15 kilometers. Thus Brocher estimates the Franciscan Formation in my study area to be 15 kilometers thick with a seismic velocity of <6.1 kilometers per second. He also suggests that the contact between the siliceous Franciscan Formation and the mafic slab of the lower crust is marked by an increase in seismic velocity to approximately 6.9 kilometers per second and represents a mechanical discontinuity. (See Figure 6).

Lawrence Livermore National Laboratory and University of California, Berkeley, have installed a seismic network (see Figure 7) consisting of eight strong ground motion seismic recorders along the San Francisco-Oakland Bay Bridge. (See Table 1). These instruments have been recording from 1996 through the present time.

The downhole sensor packages that make up the seismic network contain three Oyo HS-1 4.5 hertz (Hz) geophones and three orthogonal Wilcoxon 731 second 10 v/g accelerometers. The dynamic range of the Wilcoxon package is from a micro-g to 0.5 g acceleration, and is flat to frequency responses from 0.1 to 300 Hz. This allows recording of M=1.0 to O.5 g strong ground motion from large Bay Area earthquakes. Portable Refraction Technology 72A Data Acquisition Systems with 16 bit resolution and 200 Hz sampling are used to record the data at most sites. The data is processed and managed at University of California, Berkeley. (Hutchings, 1999).

Using data recorded from 1996 to December 1998 and a computer program known as *Simul*, a preliminary determination of the seismic velocities of the Franciscan Formation was obtained. The first step was to determine which of the events recorded could be used to form the model. The *Simul* computer program requires events with a residual less than 0.20. (See Table 2). In addition, events were chosen based on the clarity or quality of the recording and the location of the actual event. (See Figure 8). The location had to be within 40 km of the study area in order to obtain a strong reflective recording that could be used to create a more accurate profile of the Bay and occur along the San Andreas or Hayward Fault system.

In the end, only twenty-four events that occurred along the Hayward Fault and as few as eight events that occurred along the San Andreas Fault fit the criteria to be included in the study. (See Figure 9). These events and a proposed velocity model of the Franciscan Formation (Brocher, 1993) were then used as parameters to determine the seismic profile of San Francisco Bay beneath the San Francisco-Oakland Bay Bridge.

The model of the Franciscan Formation (see Figure 10), used in the study by the Simul program, was created using the seismic velocities and layer thickness data from the paper written by Thomas Brocher, USGS (1993). The *Simul* program requires that a vertical reference plane be chosen for the study area. By placing the plane near the center of the study area, more accurate velocities were obtained which could then be compared to Brocher's values.

The model was divided into four separate layers based on Brocher's proposed seismic velocities of the Franciscan Formation. The top layer of the formation has the lowest velocity of 4.5 km/s which increases to 6.1 km/s near the bottom layer of the unit. The contact between the Franciscan Formation and the lower crust is marked by a reflective layer known as the Conrad Discontinuity.

Below the discontinuity, seismic velocities increase up to 6.5 km/s. The lower crustal unit is approximately 10 km thick. Below the crust is the mantle which has a seismic velocity of 8.0 km/s.

The model of the Franciscan Formation was divided further into ten sections at 1.25 km intervals. (See Figure 11). Data from the model was entered into the *Simul* computer program. *Simul* calculated a seismic velocity for each of the ten sections.

The preliminary profile of the San Francisco Bay generated in this study was very similar to Thomas Brocher's proposed velocity model. The seismic velocity near the top of the Franciscan Formation was as low as 4.74 km/s. The velocities then increased to as high as 6.1 km/s near his proposed bottom of the Franciscan Formation. (See Figure 12). More seismic event data is needed in order to obtain a more accurate model. Once the final model is determined, it is intended be utilized in a wave propagation study of the San Francisco-Oakland Bay Bridge, currently being conducted by Lawrence Livermore National Laboratory and University of California, Berkeley as well as to redefine the geologic understanding of the area.

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SAN FRANCSICO BAY BRIDGE STATION INFORMATION

I.D.	Sensors	Latitude	Longitude	Depth h (km)	Sensor h1, h2 + 090	Recording
SFA	S-6000	37.7861	122.3893	0.00	N143E	June 98-present
BBW2	Wil-731 A, HS-1	37.79120	122.38525	0.0576	N42E	April 96-present
BBW5	Wil-731 A, HS-1	37.8018	122.3737	0.363	N142E	January 97-present
YBA	Wil-731 A, HS-1	37.8094	122.3645	0.003	N150E	June 98-present
BE2U	S-6000	37.8143	122.3582	0.00		July 96-present
BE07	Wil-731 A, HS-1	37.81847	122.34688	0.134	N117E	February 96-present
BE17	Wil-731 A, HS-1	37.82086	122.33534	0.160	N168E	August 95-present

Table 1: San Francisco-Oakland Bay Bridge Seismic Network instrumentation information

SEISMIC EVENTS

Earthquake	Time	Latitude	Longitude	Depth	Magnitude	Fault
1996/02/04	23:27:28.74	37.8798	122.3200	10.89	1.60	Hayward
1996/03/20	00:31:27.07	37.7768	122.1915	11.03	2.00	Hayward
1996/04/24	05:21:05.06	37.7657	122.1458	11.16	2.20	Hayward
1996/05/14	17:51:08.00	37.9118	122.2825	6.43	2.10	Hayward
1996/05/15	04:11:36.96	37.8017	122.1988	10.50	1.90	Hayward
1996/05/30	02:50:45.66	37.8712	122.2387	11.16	2.00	Hayward
1996/05/31	08:36:47.55	37.8745	122.2415	9.51	1.80	Hayward
1996/10/31	23:09:43.37	37.7553	122.1667	9.46	2.30	Hayward
1996/12/24	16:16:54.79	37.7355	122.5455	6.56	2.20	San Andreas
1996/12/31	05:39:41.80	37.8787	122.2495	9.85	1.50	Hayward
1997/02/20	13:43:38.60	37.8415	122.2280	5.61	1.80	Hayward
1997/03/11	06:30:16.33	37.7123	122.5663	5.22	3.50	San Andreas
1997/03/11	06:32:36.58	37.7137	122.5653	4.96	2.40	San Andreas
1997/04/03	17:31:22.25	37.8668	122.2388	10.01	1.90	Hayward
1997/05/02	11:30:37.62	37.7062	122.5175	5.20	2.50	San Andreas
1997/06/19	00:35:29.87	37.7795	122.5942	3.08	2.50	San Andreas
1997/06/19	04:11:42.66	37.7795	122.5963	2.96	2.20	San Andreas
1997/06/25	01:11:34.86	37.8477	122.2308	4.75	1.10	Hayward
1997/06/25	03:13:59.46	37.8547	122.2253	8.09	1.60	Hayward
1997/08/17	18:41:54.17	37.8682	122.2390	10.07	1.30	Hayward
1997/08/31	00:24:13.99	37.7360	122.0900	9.42	2.92	Hayward
1997/09/08	00:10:38.00	37.8595	122.2328	9.60	1.40	Hayward
1997/10/27	14:30:50.65	37.7265	122.5473	10.15	2.90	San Andreas
1998/04/10	04:07:49.46	37.8670	122.2427	10.34	1.50	Hayward
1998/05/09	04:27:07.86	37.7557	122.5663	7.23	2.40	San Andreas

Earthquake	Time	Latitude	Longitude	Depth	Magnitude	Fault
1998/07/25	07:57:47.88	37.8672	122.2377	12.06	2.70	Hayward
1998/10/15	23:52:41.69	37.8640	122.2400	10.95	1.90	Hayward
1998/10/20	12:46:18.87	37.8777	122.2455	10.03	2.10	Hayward
1998/11/03	06:02:16.32	37.8758	122.2433	9.53	2.40	Hayward
1998/11/22	09:55:29.60	37.7402	122.1257	7.65	2.40	Hayward
1998/12/04	12:16:07.76	37.9200	122.2898	6.83	4.12	Hayward

Table 2: Events used to generate seismic profile.

SAN FRANCISCO BAY

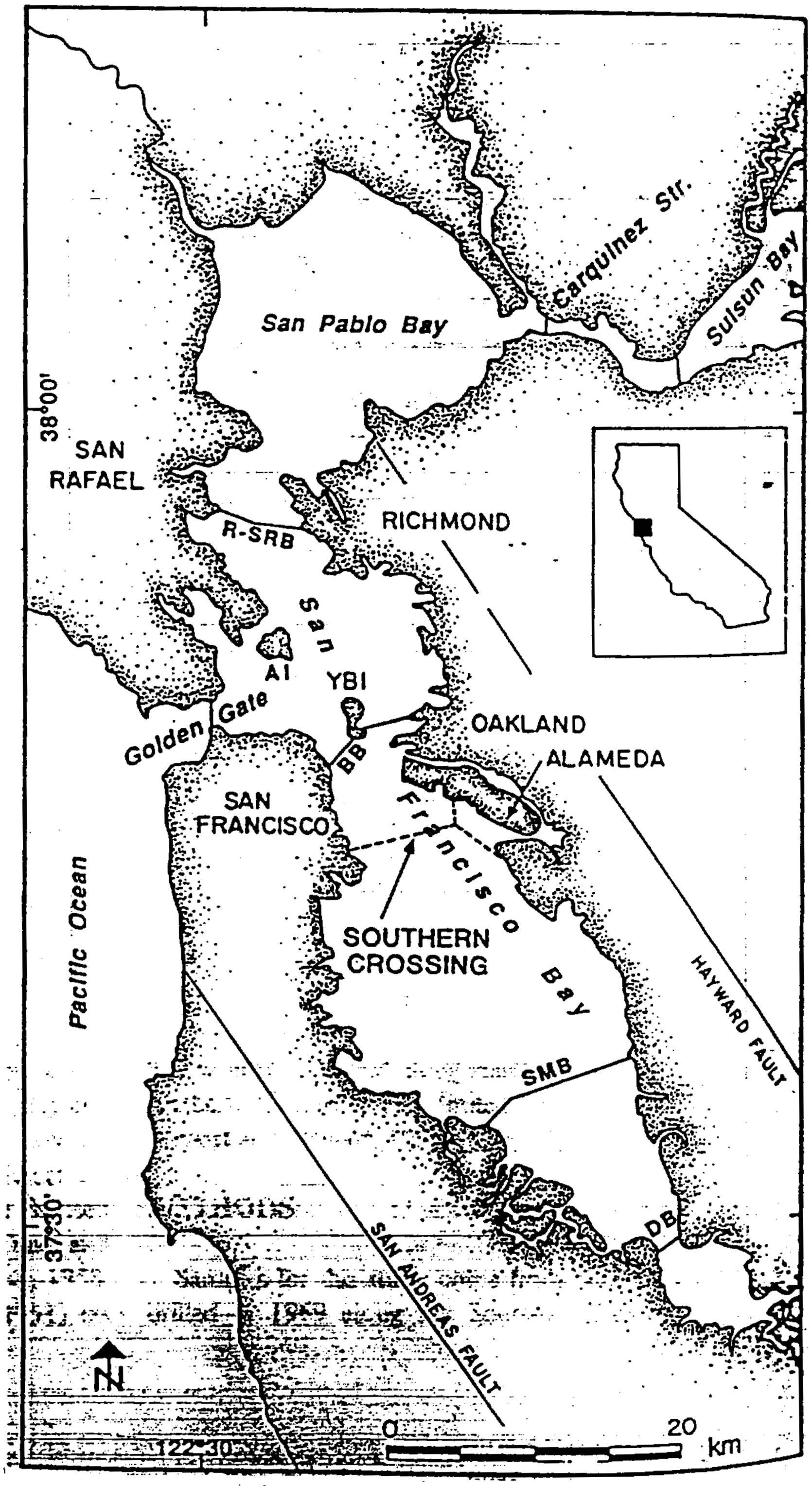
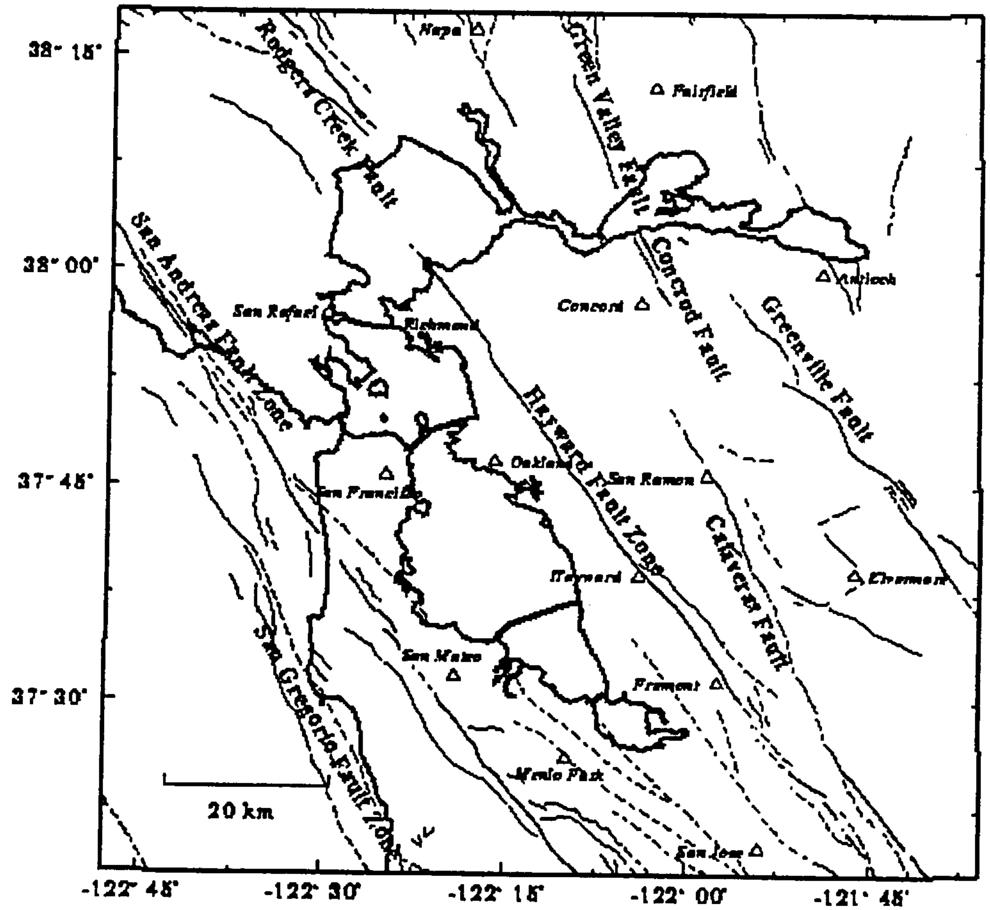


Figure 1: Map of San Francisco Bay, California. (Sloan, 1992).

MAP OF THE SAN FRANCISCO BAY AREA COMPLEX FAULT SYSTEMS



Major Bay Area Faults

Figure 2: Map of San Francisco Bay Area. The San Andreas Fault marks the west boarder of the San Francisco Bay Basin and the Hayward fault marks the eastern boarder.

ROUTE OF THE MAIN RIVER OVER TIME

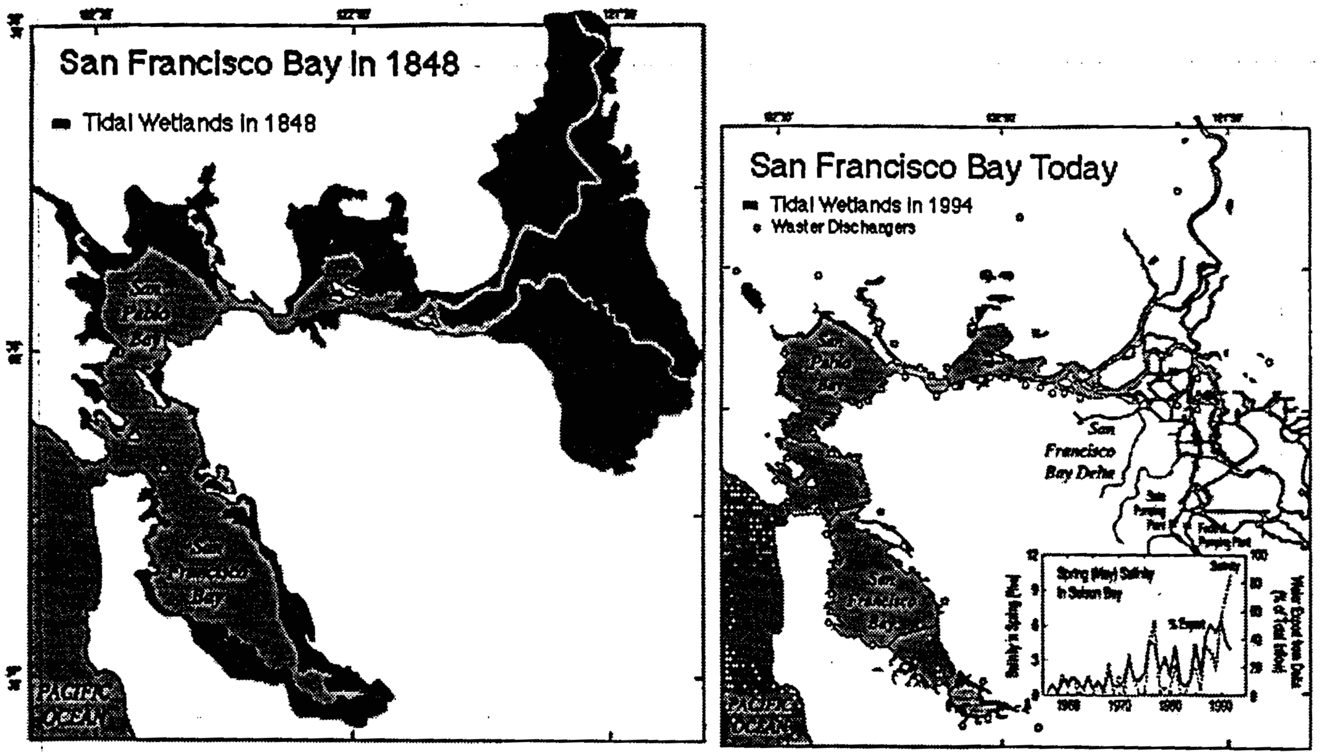


Figure 3: Map of the San Francisco Bay estuary at the confluence of the Sacramento and San Joaquin Rivers. The main route of the rivers remains unchanged over time indicating that deformation and uplift of the area occurred slowly.

GEOLOGIC PROFILE OF SAN FRANCISCO BAY BENEATH THE SAN FRANCISCO-OAKLAND BAY BRIDGE

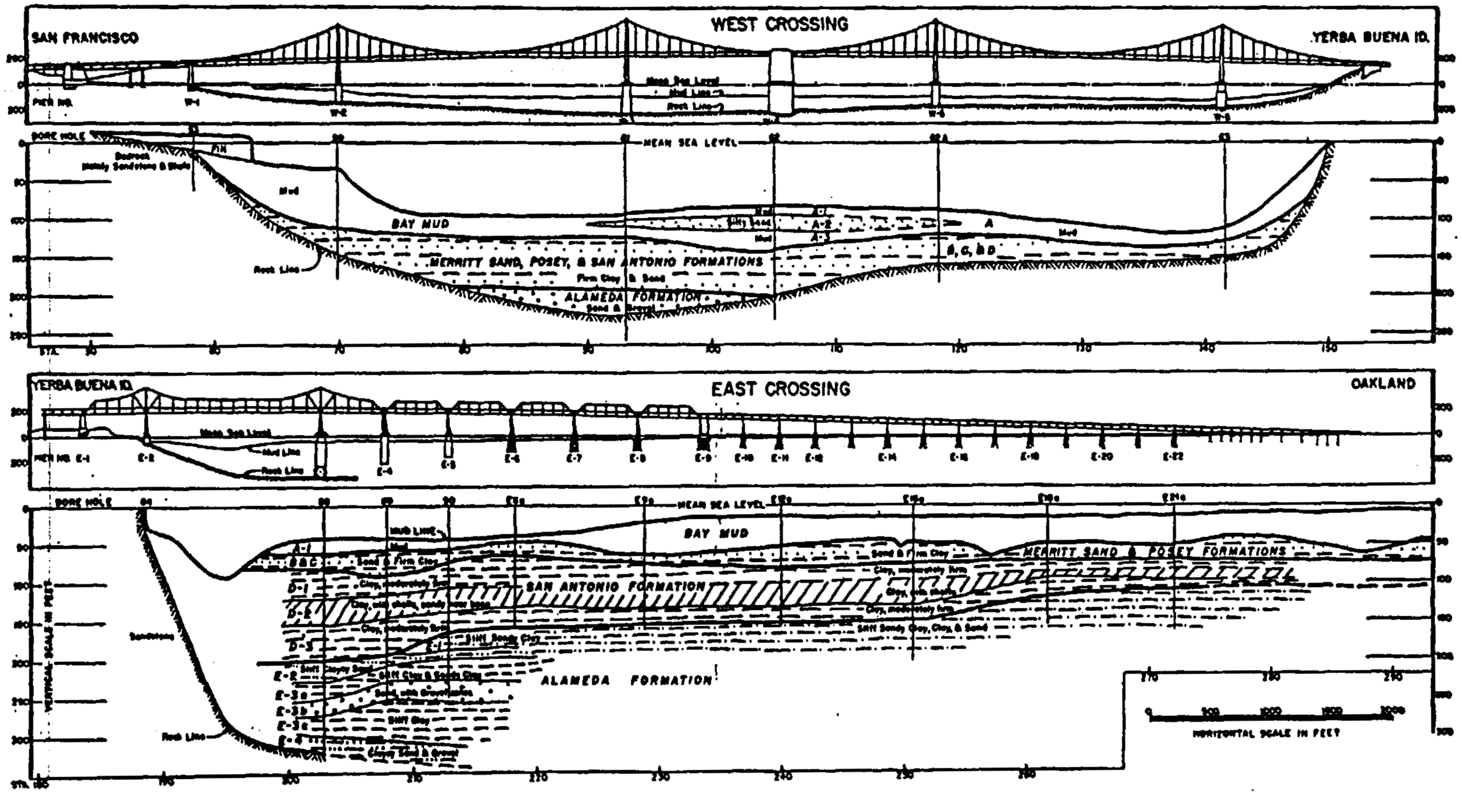


Figure 4: Geologic cross section of the sediments above the Franciscan Formation beneath the San Francisco-Oakland Bay Bridge. (Trask, 1951).

BASIX PRELIMINARY SCHEMATIC INTERPRETATION OF PROPOSED VELOCITY MODEL

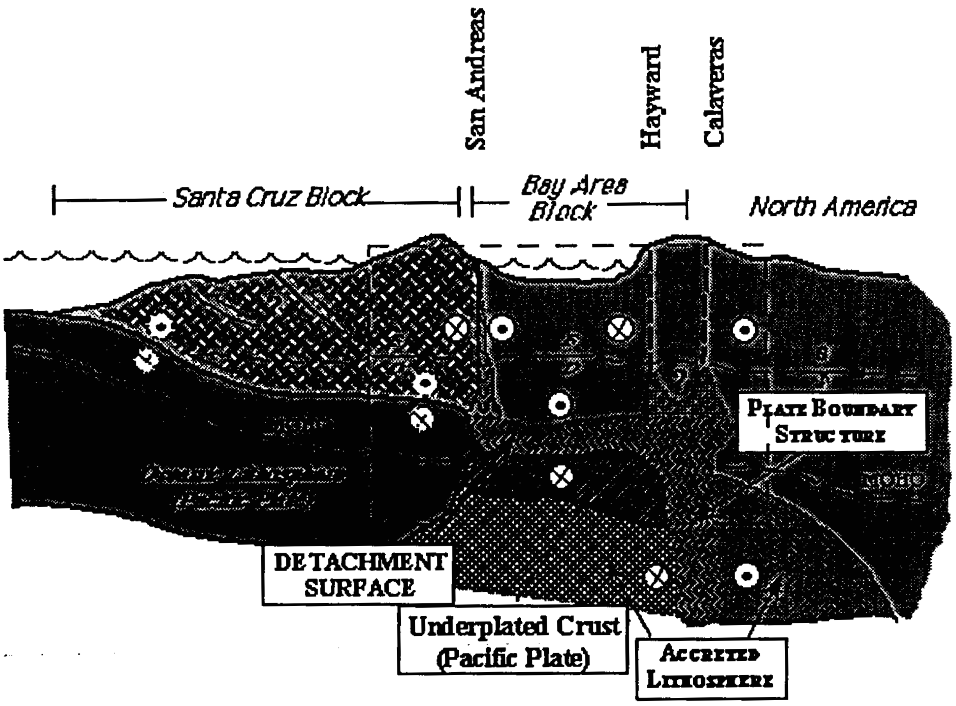


Figure 5: Preliminary schematic interpretation of the velocity model assuming that the lower crustal reflector represents a detachment (Dashed rectangle shows region covered by velocity model). (Brocher, 1993).

VELOCITY MODEL PROPOSED BY THOMAS BROCHER, USGS (1993)

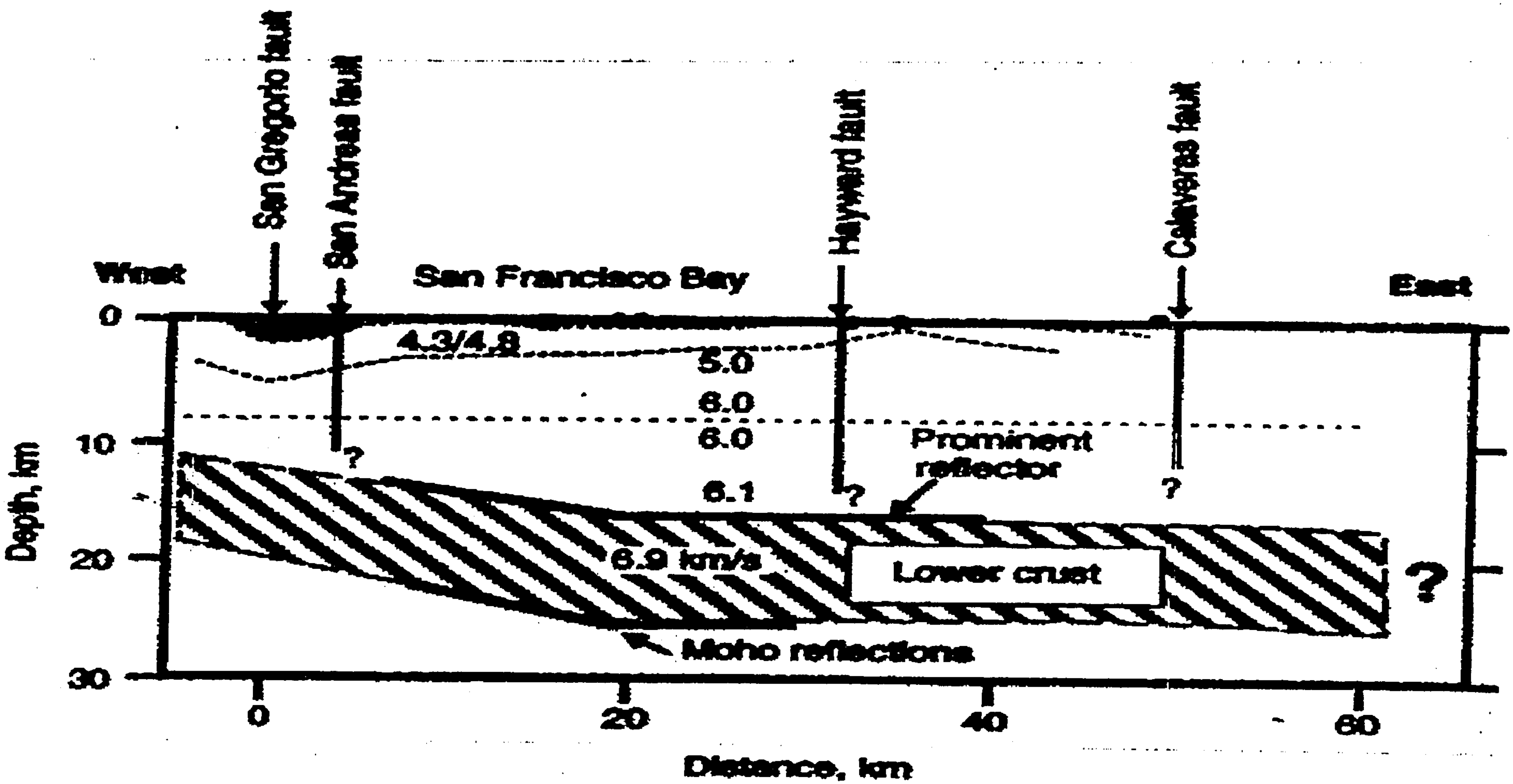


Figure 6: Proposed velocity profile determined by seismic data obtained through BASIX study in 1991. (Brocher, 1993).

SAN FRANCISCO-OAKLAND BAY BRIDGE SEISMIC NETWORK

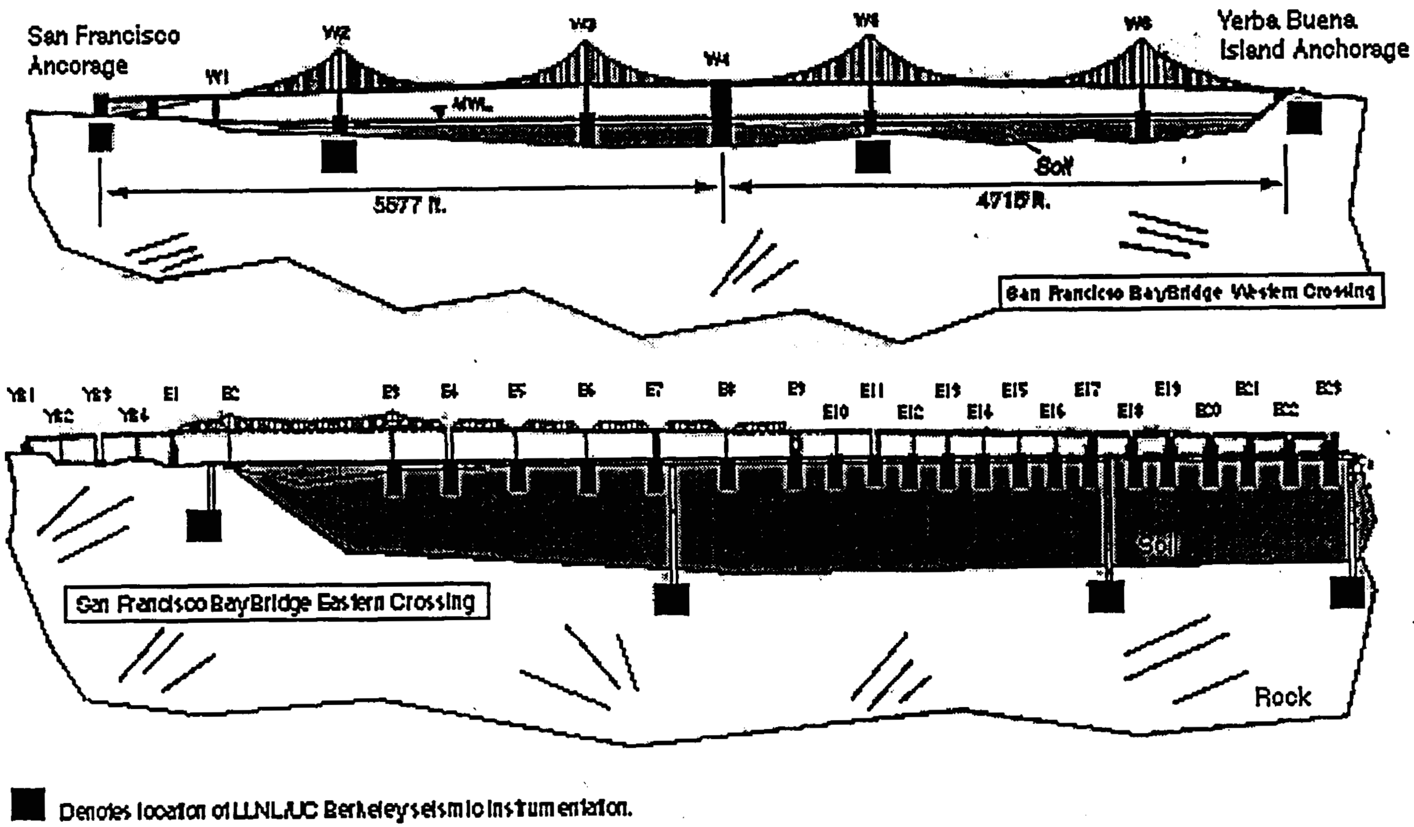


Figure 7: Bay bridge seismic network installed by Lawrence Livermore National Laboratory (1996) and monitored by University of California, Berkeley.

EARTHQUAKE ON THE HAYWARD FAULT
December 4, 1998
M=4.12

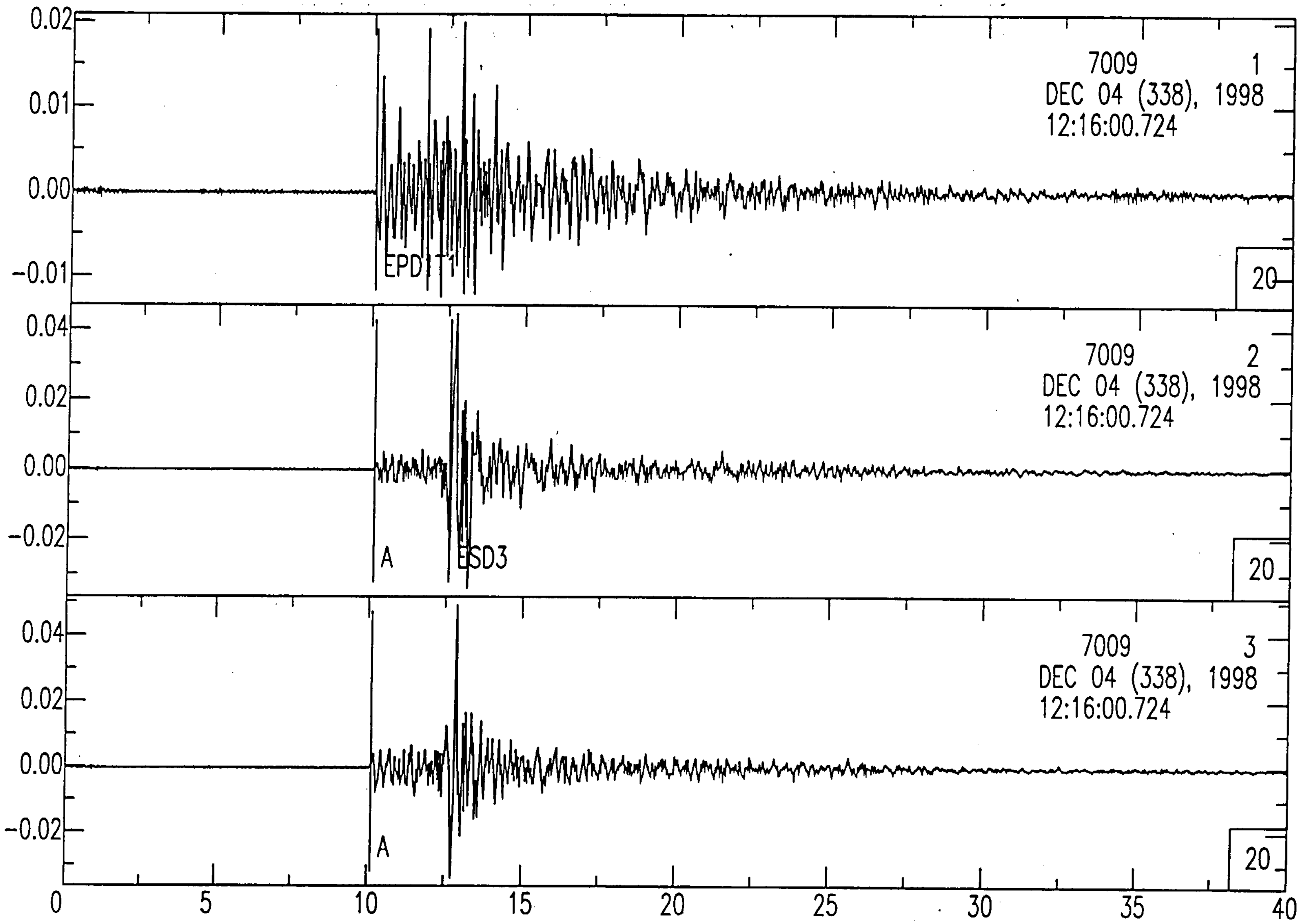


Figure 8: Seismograph of event used in study.

/u0/turpin/Bridge/BBW5/9812041216 f001.sgf

Wed Aug 18 15:32:20 1999

Bay Bridge Recordings

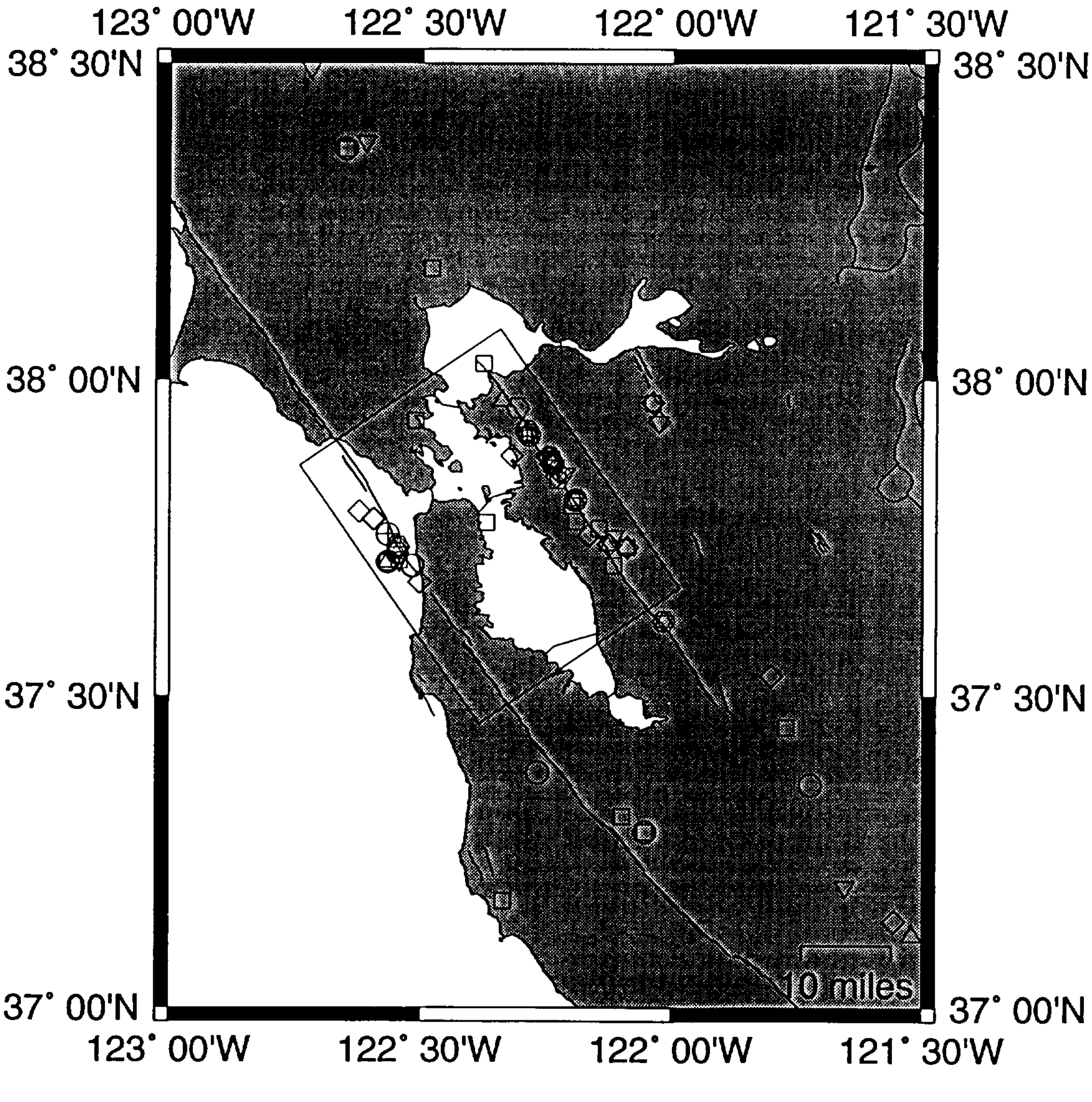


Figure 9: Map of study area. Seismic events used occurred along either the Hayward or San Andreas Fault and within 40 km of the Bay Bridge.

BLOCK MODEL PROPOSED BY THOMAS BROCHER, USGS OF THE SAN FRANCISCO BAY BENEATH THE BAY BRIDGE

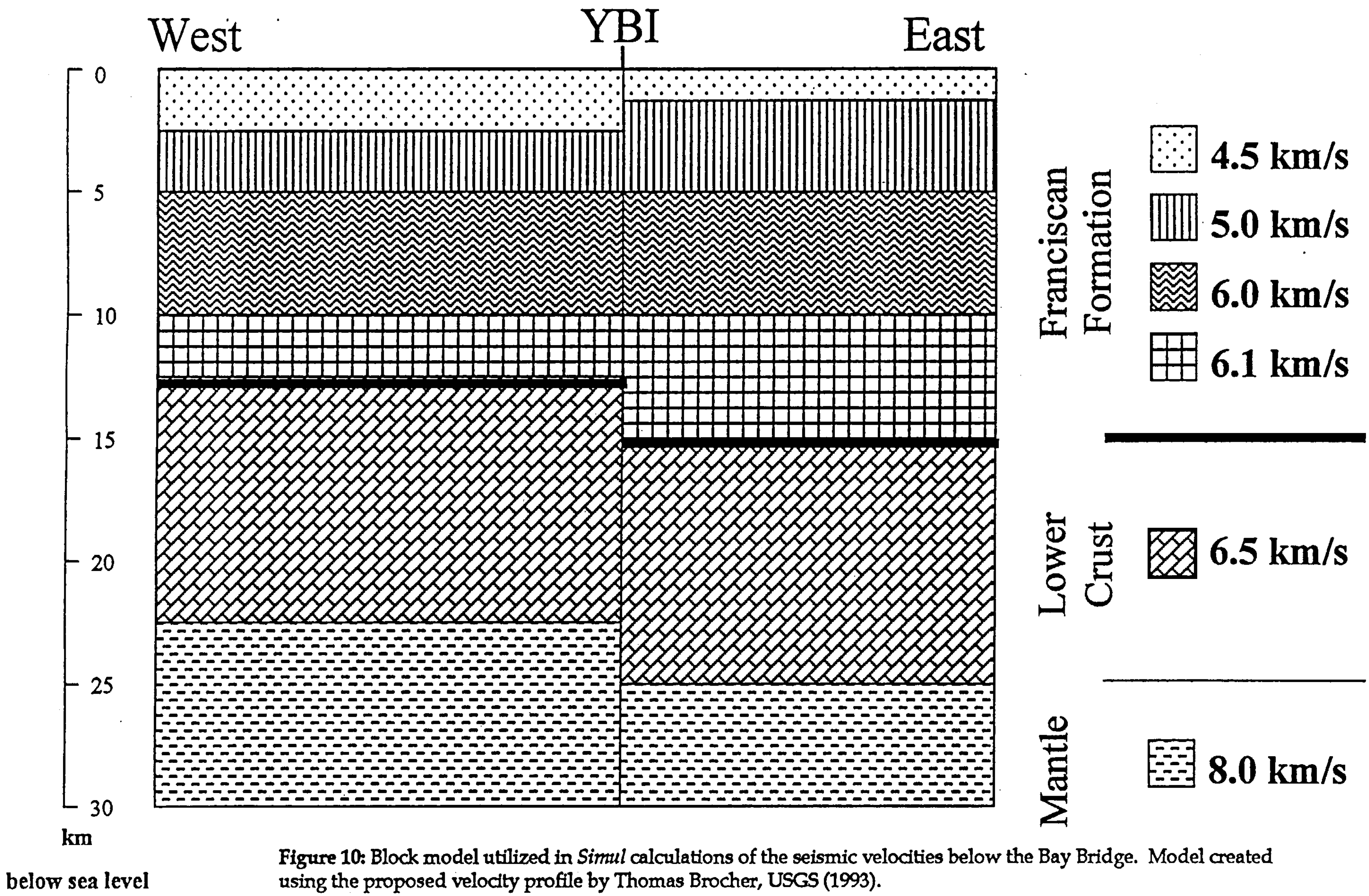


Figure 10: Block model utilized in *Simul* calculations of the seismic velocities below the Bay Bridge. Model created using the proposed velocity profile by Thomas Brocher, USGS (1993).

BLOCK MODEL UTILIZED IN *SIMUL PROGRAM*

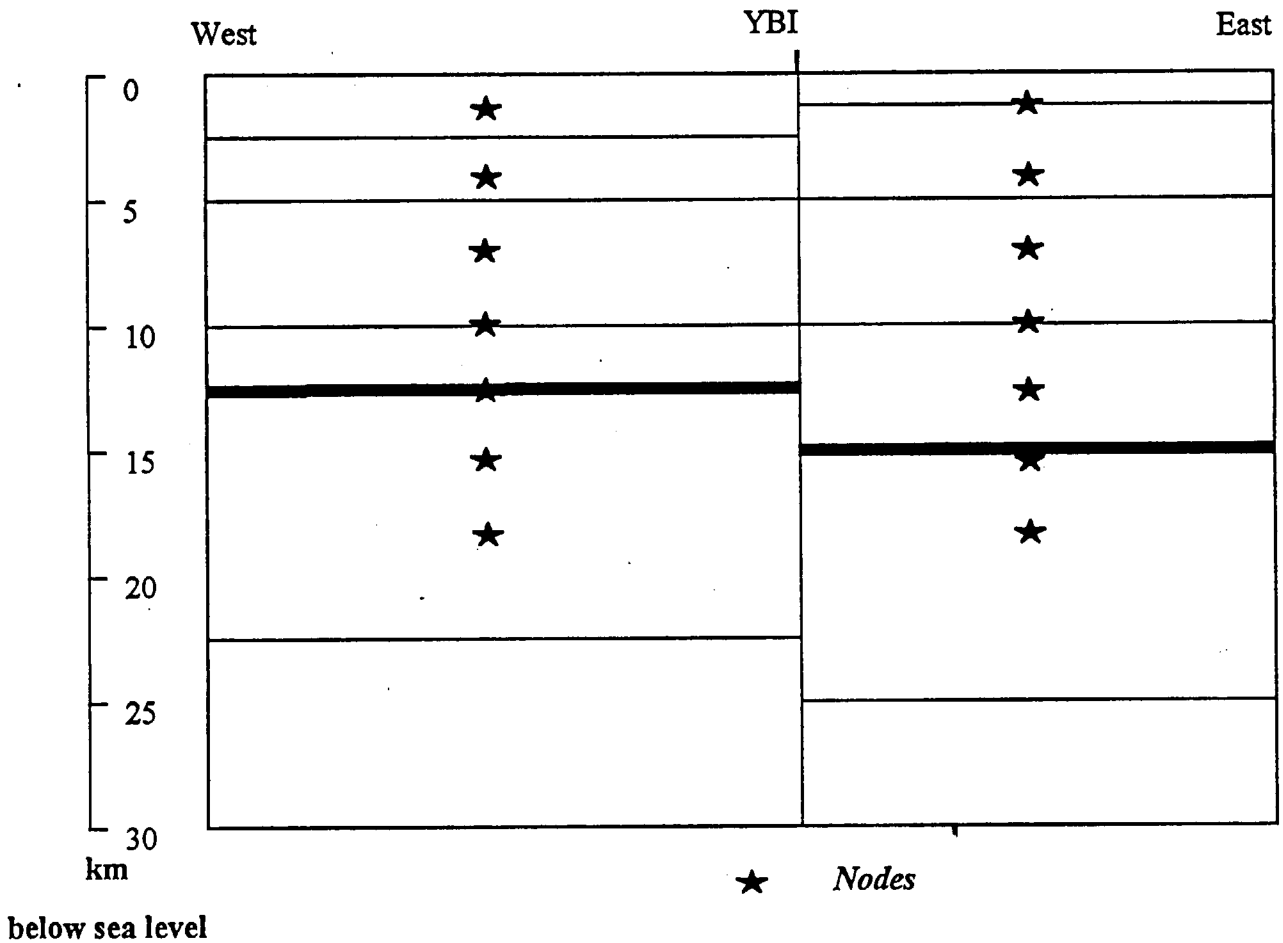


Figure 11: Nodes were placed at 1.25 km intervals within the block model. At each node a seismic velocity will be determined using the *Simul* computer program.

PRELIMINARY SEISMIC PROFILE OF THE SAN FRANCISCO BAY BENEATH THE SAN FRANCISCO-OAKLAND BAY BRIDGE

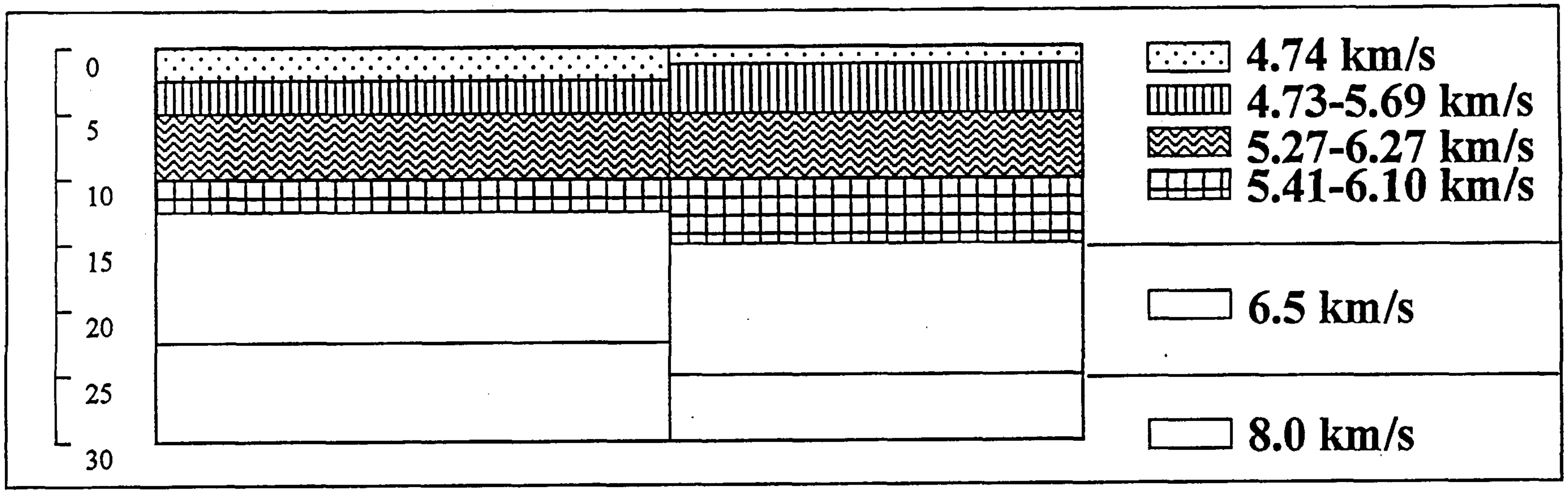


Figure 12: Preliminary velocity profile of the Franciscan Formation obtained using seismic events recorded by the Bay Bridge Seismic Network from 1996 to December of 1998. Events occurred along the San Andreas or Hayward fault within 40 km of the study area.